Analysis of Sources of Variability in Runoff Plots Studies Using a Numerical Model: A Case Study From a 40 Fallow Plots Experiment

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Abstract

Runoff volumes from plots can be quite variable. These variations can be important for understanding the hydrologic system, and also to evaluating the effectiveness of infiltration and runoff prediction models. We investigated the sources of variability among 40 replications in a previously reported experiment on fallow plots. A numerical model was calibrated using data from the experiment and from other published data. Approximately 70% of the observed variation among the replicated plots could be explained by the spatial variabilities of hydraulic conductivity, surface storage, and the depth to claypan. Changes in the relative differences in runoff among plots may be explainable by the modification of the spatial distribution of hydraulic conductivity and surface storage during tillage. The introduction of these sources of variability in the model formulation produced a realistic description of the variance of the observed values of runoff, as well as a relatively clear delineation between the explained and unexplained variability. These results can serve as an index of model performance in predicting observed data.
Keywords. Runoff, Infiltration, Variability, Numerical models, Hydraulic conductivity.

Introduction

Data from runoff plots show a large variability. Rüttimann et al. (1995), and Wendt et al. (1986) reported a coefficient of variation, CV, for season runoff ranging from 30 to 50%. It has been suggested that the magnitude of the observed CV should decrease as a function of increasing plot size, however, Rüttiman et al. (1995) analyzed published CV values for plots of different areas and did not find such a relationship in those data. Attempts to relate the observed differences in runoff among the replications to differences in soil properties were unsuccessful in the study of Wendt et al. (1986). In the study of Wendt et al. (1986), the relative differences between replications did not persist in time, a result corroborated by Rüttiman et al. (1995). Wendt et al. (1986) attributed this, in part at least, to the occurrence of tillage operations. The consequence of this relatively high level of unexplained CV is that there must be a sufficient number of replications included in the experimental design in order to have statistical significance of the results, and that small differences in runoff among treatments are difficult to detect. The large variation of replicates is important also in the evaluation of the performance of simulation models. It is difficult to delineate that portion of the observed error coming from the model prediction from that coming from the unexplained variability (Nearing, et al., 1999). Freeze (1980) reported an estimation of the spatial variability of soil properties or profile characteristics, and using a numerical model and Monte-Carlo simulations studied their impact in the variation of runoff at hillslope scale. Those results showed how this spatial variation may lead to significant differences among similar hillslopes. Exists empirical evidence of large CV values under field conditions for infiltration rates (Star, 1990) and hydraulic conductivity, K_s (Mohanty et al., 1994). The objective of this study was to analyze and understand the variation of runoff from 40 replicated plots presented in a previously published work using a numerical model and other measured or published values for the spatial variation of soil properties. The goal was to improve our understanding of why large variabilities in runoff occur for replicated field plots, and to improve the extrapolation and prediction capabilities of the numerical model by taking into account the spatial variability of the more relevant soil properties.

Materials and Methods

This study uses data previously published by Wendt et al. (1986) from a 40 plot experiment located near Kingdom City, MO. Each plot was 3.2-m wide and 27.4-m long, oriented parallel to a 3 to 3.5% slope. The soil

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was a Mexico silt loam, which has a slowly permeable layer of illuvial clay (claypan) beginning at depths of 0.2-0.3m. A complete description of this experiment can be found in Wend et al. (1986)

An infiltration-runoff model was used to analyze the differences due to the spatial variability of hydraulic conductivity, surface storage, and depth to claypan. Briefly, the model has two major components: (1) An infiltration algorithm based on the Green and Ampt model. The model divided the area into square cells of 1 x 1m, and used distributed parameters of Ks, surface storage, and depth to claypan for every cell. (2) Surface runoff was computed by routing the excess water in the cell using the slope and aspect of each cell. The model takes into account runoff and run-on between cells. Detailed descriptions of this model appear in Gómez et al.[a] (2000). Model calibration was made for an average soil profile for the site. Surface storage (updated between events), Manning's coefficient, soil properties, depth to claypan, plot slope and rate and decrease of surface hydraulic conductivity due to crusting were parameters to the model, that considered four different soil layers. The initial soil moisture content for each event was also considered. The method proposed by Freeze (1980) was used to produce maps of spatially distributed surface storage, depth to claypan, and K_s. Different maps 250x165m in size, representing the entire area containing the forty plots, were generated. From the previous maps forty maps of 3x28-m were selected (one per plot) according to the plot configuration, size, and spacing in the field experiment. A different map for K_s and surface storage was generated and used for any group of rainfall events following a tillage operation, a total of six tillages were performed during the experiment. The required values for the standard deviation of K_s, surface storage, and depth to claypan were obtained from Mohanty et al. (1994), Wend et al. (1986) and Hansen et al. (1999) with a CV for those variables of 125, 9.1 and 17 % respectively. Further details appear in Gomez et al.[b] (2000). The value of the freshly tilled, hydraulic conductivity was adjusted by minimization of mean square error between observed and simulated runoff using the 25 events. The observed regression between observed and simulated runoff is not significantly different at the 95% probability level of the 1:1 line of perfect agreement.

Results

We generated a map for K_s, depth to claypan, and surface storage for each of the forty plots as discussed above. Figures 1 shows the CV using K_s or surface storage as the source of variation, and the average spatially uniform value for the other two variables. The spatial variability of K_s results in the greatest CV of the runoff and maintains its significance for the large runoff events. Differences due to surface storage are relatively important in small runoff events and less so in the large ones. Depth to claypan appears as a source of variability only in events related to high initial soil moisture content or large infiltration infiltration, with values of CV of runoff ranging from 0 to 10% (data not shown).
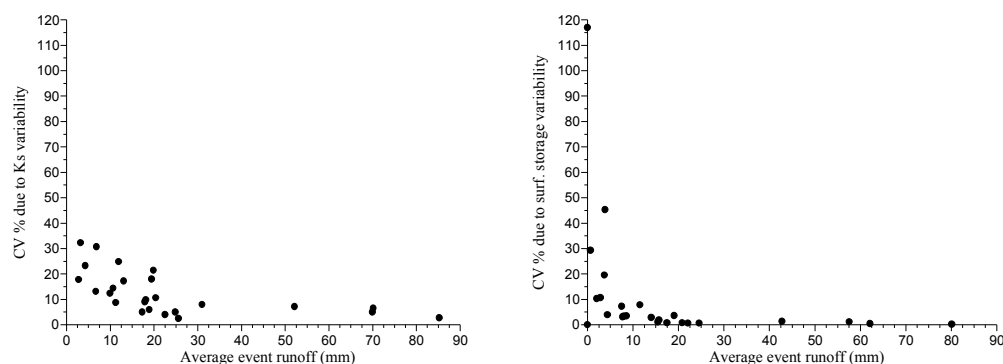

Figure 1. CV due to K_s or surface storage.

When the three sources were considered together we obtained the CV for runoff shown in Figure 2. The magnitude of CV was greater for the smaller runoff events, but still significant, at approximately 20%, in the larger runoff events. The simulated CV was only slightly smaller than observed, and primarily so for small runoff events.
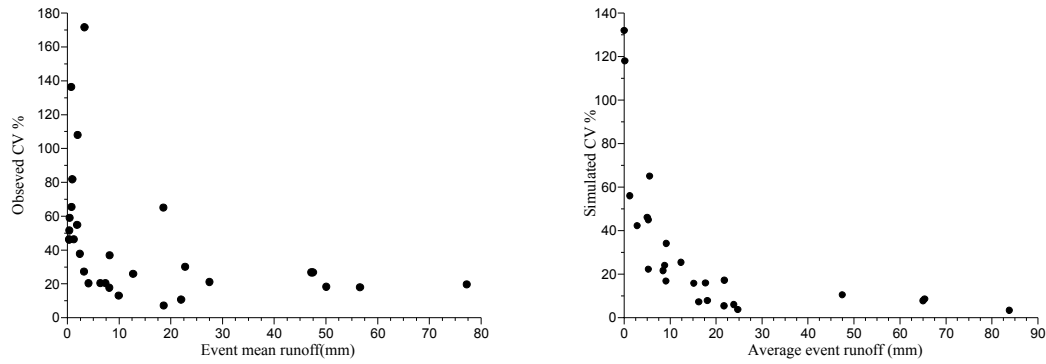
Figure 2. Observed and simulated CV.

Figure 3 shows the observed and simulated time stability parameter, λ (Starr 1990) and their 90% confidence interval bars. The parameter λ should be interpreted as an index of the persistence in time of the relative differences among plots. Many of the plots range between the 90% confidence intervals showing no or very small significant differences, which is interpreted as a lack of stability in time of the relative differences in runoff among the plots. This trend was observed in the simulated λ too. This was true only when a new set of K_s and surface storage map was generated in conjunction with each tillage operation, and no when a single map was used for any plot for the 25 events, assuming no modification of spatial distribution due to tillage (data not shown).
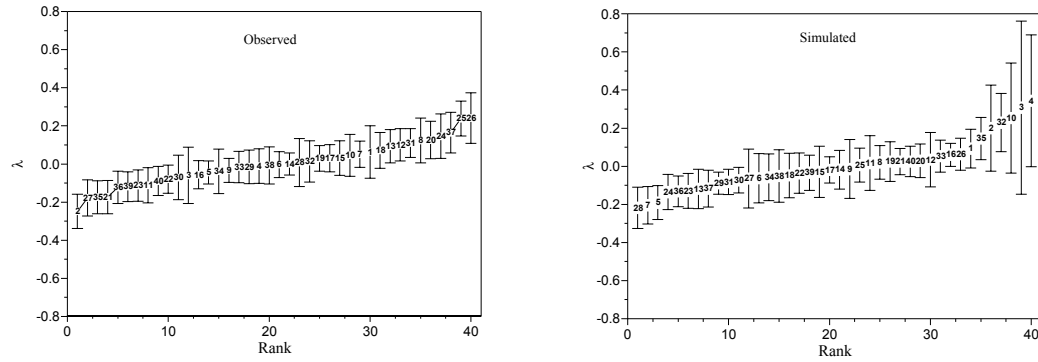

Figure 3: Observed and simulated λ.

Discussion

We found that the numerical approach explains approximately 70% of the observed average CV: 36.8% by K_s, 29.6% by surface storage, and 3.8% by depth to a claypan The differences between observed and simulated variations in runoff can be explained by various factors. First, in our numerical study, the CV attributed to measurement error of runoff and spatial variation of rainfall was not considered. The errors for both factors were estimated for this experiment as ±2% for runoff and ±2.3% for rainfall (Wendt et al., 1986), which translates to approximately 11% of the total observed CV for runoff for these plots. A second reason is that the approach used for calibrating K_s tends to increase simulated runoff for low runoff events in comparison to the observed ones, leading to lower simulated CV values. We used this approach to assure a non-biased simulation. A third factor is that published values from other locations were used for generating spatial variability, which will vary somewhat from this particular experimental area. Finally, some simplifications are assumed in the numerical model, for instance, spatially varying crusting is not incorporated into the model. Despite these

considerations, the agreement between observed and simulated values is qualitatively good, in that smaller events showed a much greater variation than did the larger events.

Variations in hydraulic conductivity, K_s, was the most important contributor to runoff variability of the three factors analyzed in agreement with previous works, e.g. Freeze (1980), or Gupta, et al. (1998). The depth to claypan was a relatively minor contributor to runoff CV, and will usually be only a sporadic source of runoff variation. The third factor is the variation in surface storage. Its contribution to the variation is more important in low runoff events, as would be expected. Surface storage may also be an important contributor to variance in events where there are several peaks of rainfall intensities with transition periods between them in which surface water infiltrates. The instability in time of the differences in runoff among plots could not be explained without assuming that tillage modifies the spatial distribution of K_s and surface storage .The modification of the spatial distribution of K_s by tillage has been reported by Mohanty et al (1994), and it is due to the fluctuations that exist in soil conditions, tractor speed, tillage depth, and applied stress during tillage operations. This fact supports our assumption that surface storage is related to surface microrelief and is modified as a function of tillage too.

In this work, though fairly homogeneous soil conditions existed, the CV was relatively large. These conditions translate to a need for a longer measurement duration for the experiment or in the absence of that, the expectation to obtain significant results only when treatment differences are very large (Nearing et al., 1999). An integrated approach in which the plot measurements are combined with field surveys to assess the variability in the soil properties could increase the performance of runoff experiments. This could allow the detection of unexplained differences among plots and the generation of confidence intervals for the different treatments using numerical models. This approach allows, too, for a more realistic description of the real system, as the resultant output is not just a single estimation of runoff but rather a set of output values as is observed in field experiments. This allow us to consider in the evaluation not only the agreement between average observed and calculated values, but also the distribution and the evolution in time of the differences within replications. A more precise evaluation of the model performance is also made possible, with a clearer distinction made between variation that can be attributed to the model itself from the variation that is intrinsic to the system.

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